Lecture 15

Applications of passive remote sensing using emission: Remote sensing of sea surface temperature (SST)

Objectives:
1. SST retrievals from passive infrared remote sensing.
2. Microwave vs. IR SST retrievals.

Required reading:
G: 7.2

Additional/advanced reading:
Electronic lecture on SST: http://see.gsfc.nasa.gov/edu/SEES/ocean/oc_class.htm


1. SST retrievals from passive infrared remote sensing

Principles:
measure IR radiances in the “atmospheric window” and correct for contribution from “clear” sky by using multiple channels (called “split-window” technique)

Using Eq.[14.10] , we can write IR radiance at TOA:

$$I_A^\dagger(0; \mu) = B_A(\tau^*) \exp\left(-\frac{\tau^*}{\mu}\right) + \frac{1}{\mu} \int_0^{\tau^*} \exp\left(-\frac{\tau'}{\mu}\right) B_A(\tau') d\tau'$$  [15.1]
Let’s re-write this equation using the transmission function \( T_\lambda (\tau^*, \mu) = \exp\left(-\frac{\tau^*}{\mu}\right) \) and that

\[
I_\lambda^{\hat{\tau}}(0; \mu) = B_\lambda (T_{\text{sur}}) T_\lambda (\tau^*, \mu) + B_\lambda (T_{\text{atm}})[1 - T_\lambda (\tau^*, \mu)]
\]

where \( T_{\text{atm}} \) is an “effective” blackbody temperature which gives the atmospheric emission

\[
B_\lambda (T_{\text{atm}}) = [1 - T_\lambda (\tau^*, \mu)]^{-1} \frac{1}{\mu} \int_0^{\tau^*} \exp\left(-\frac{\tau'}{\mu}\right) B_\lambda (\tau') d\tau'
\]

We want to eliminate the term with \( T_{\text{atm}} \) in Eq.[15.2]. Suppose we can measure IR radiances \( I_1 \) and \( I_2 \) at two at the adjacent wavelengths \( \lambda_1 \) and \( \lambda_2 \)

\[
I_1^{\hat{\tau}} = B_1 (T_{\text{sur}}) T_1 (\tau_1^*, \mu) + B_1 (T_{\text{atm}})[1 - T_1 (\tau_1^*, \mu)]
\]

\[
I_2^{\hat{\tau}} = B_2 (T_{\text{sur}}) T_2 (\tau_2^*, \mu) + B_2 (T_{\text{atm}})[1 - T_2 (\tau_2^*, \mu)]
\]

**NOTE:** two wavelengths need to be close to neglect the variation in \( B_\lambda (T_{\text{atm}}) \)

Let’s apply the Taylor’s expansion to \( B_\lambda (T) \) at temperature \( T = T_{\text{atm}} \)

\[
B_\lambda (T) = B_\lambda (T_{\text{atm}}) + \frac{\partial B_\lambda (T)}{\partial T} (T - T_{\text{atm}})
\]

Using this expansion for both wavelengths, we have

\[
B_1 (T) \approx B_1 (T_{\text{atm}}) + \frac{\partial B_1 (T)}{\partial T} (T - T_{\text{atm}})
\]

\[
B_2 (T) \approx B_2 (T_{\text{atm}}) + \frac{\partial B_2 (T)}{\partial T} (T - T_{\text{atm}})
\]

and thus, eliminating \( T - T_{\text{atm}} \), we have

\[
B_2 (T) \approx B_2 (T_{\text{atm}}) + \frac{\partial B_2 (T)}{\partial T} \frac{\partial T}{\partial B_1 (T)} [B_1 (T) - B_1 (T_{\text{atm}})]
\]

Let’s introduce brightness temperatures for these two channels \( T_{b,1} \) and \( T_{b,2} \)
\[ I_1 = B_1(T_{b,1}) \text{ and } I_2 = B_2(T_{b,2}) \]
and apply [15.9] to \( B_2(T_{b,2}) \) and to \( B_2(T_{sur}) \)
\[
B_2(T_{b,2}) \approx B_2(T_{atm}) + \frac{\partial B_2(T)}{\partial T} \bigg[ B_1(T_{b,2}) - B_1(T_{atm}) \bigg] \]
[15.10]
and
\[
B_2(T_{sur}) = B_2(T_{atm}) + \frac{\partial B_2(T)}{\partial T} \bigg[ B_1(T_{sur}) - B_1(T_{atm}) \bigg] \]
[15.11]

Let’s substitute the above expressions for \( B_2(T_{b,2}) \) and to \( B_2(T_{sur}) \) in Eq.[15.5]
\[
B_2(T_{atm}) + \frac{\partial B_2(T)}{\partial T} \bigg[ B_1(T_{b,2}) - B_1(T_{atm}) \bigg] = \]
[15.12]
\[
= T_2 \left\{ B_2(T_{atm}) + \frac{\partial B_2(T)}{\partial T} \bigg[ B_1(T_{sur}) - B_1(T_{atm}) \bigg] \right\} + B_2(T_{atm})[1-T_2] \]
where \( T_1 \) and \( T_2 \) are transmissions in the channels 1 and 2.

Eq.[15.12] becomes
\[
B_1(T_{b,2}) = B_1(T_{sur})T_2 + B_1(T_{atm})[1-T_2] \]
[15.13]

Using Eq.[15.4], we can eliminate \( B_1(T_{atm}) \)
\[
B_1(T_{sur}) = I_1 + \gamma[I_1 - B_1(T_{b,2})] \]
[15.14]
where \( \gamma = \frac{1-T_1}{T_1 - T_2} \); (\( T_1 \) and \( T_2 \) are transmissions in the channels 1 and 2).

Performing liberalization of Eq.[15.14]
\[
T_{sur} \approx T_{b,1} + \gamma[T_{b,1} - T_{b,2}] \]
[15.15]

The principle of the SST retrieval algorithm:
SST is retrieved based on the linear differences in brightness temperatures at two IR channels. Two channels are used to eliminate the term involving \( T_{atm} \) and solve for \( T_{sur} \).

**NOTE:** Clouds cause a serious problem in SST retrievals => need a reliable algorithm to detect and eliminate the clouds (called a cloud mask).
One needs to distinguish the bulk sea surface temperature and skin sea surface temperature:

**Bulk (1-5 m depth) SST measurements:**

1. Ships
2. Buoys (since the mid-1970s): buoy SSTs are much less noisy than ship SSTs

   Data from buoys are included in the SST retrieval algorithm

**Skin SST from infrared satellite sensors:**

- SR (Scanning Radiometer) and VHRR (Very High Resolution Radiometer) both flown on NOAA polar orbiting satellites: since mid-1970
- AVHRR (Advanced Very High Resolution Radiometer):
  - since 1978 (4 channels, started on NOAA-6)
  - since 1988 (5 channels, started on NOAA-11)

### Table 15.1

<table>
<thead>
<tr>
<th>AVHRR Channel</th>
<th>Wavelength (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.58 - 0.68</td>
</tr>
<tr>
<td>2</td>
<td>0.72 - 1.10</td>
</tr>
<tr>
<td>3</td>
<td>3.55 - 3.93</td>
</tr>
<tr>
<td>4</td>
<td>10.3 - 11.3</td>
</tr>
<tr>
<td>5</td>
<td>11.5 - 12.5</td>
</tr>
</tbody>
</table>

### AVHRR MCSST (Multi-Channel SST) algorithm:

\[
\text{SST} = a T_{h,4} + \gamma(T_{h,4} - T_{h,5}) + c
\]

where \(a\) and \(c\) are constants.

\[
\gamma = \frac{1 - T_4}{T_4 - T_5}, \quad T_4 \text{ and } T_5 \text{ are transmission function at AVHRR channels 4 and 5} \]
AVHRR NLSST (Non-Linear SST) operational algorithm (Version 4.0):

\[
\text{SST} = a + b \, T_{b,4} + c(T_{b,4} - T_{b,5}) \, \text{SST}_{\text{guess}} + d(T_{b,4} - T_{b,5}) \left[ \sec(\theta_{\text{sat}}) - 1 \right]
\]  

[15.17]

where

- \( \text{SST}_{\text{guess}} \) if a first-guess SST;
- \( T_{b,4} \) and \( T_{b,5} \) are brightness temperature measured by AVHRR channels 4 and 5;
- \( a, b, \) and \( c \) are coefficients that calculated for two different regimes of \( (T_{b,4} - T_{b,5}) \):
  - one set for \( (T_{b,4} - T_{b,5}) \leq 0.7 \)
  - another set for \( (T_{b,4} - T_{b,5}) > 0.7 \)

The coefficients \( a, b, \) and \( c \) are estimated from regression analyses using co-located in situ buoy and satellite measurements (called “matchups”).

**Alternative approach**

(used in the SST retrieval algorithm in ATSR (Along-Track Scanning Radiometer) on ERS; ATSR has 4 channels 1.6, 3.7, 10.8 and 12 \( \mu \)m)

\[
\text{SST} = a_0 + \sum a_i T_{b,i}
\]

[15.18]

Coefficients \( a_i \) are calculated from a fit to a radiative transfer model instead of in situ observations as in the AVHRR algorithm.

**NOTE**: both algorithms work for cloud-free pixels => cloud mask is required

- Examples of SST retrieved from AVHRR.

![Temperature (Celsius)](June_1996.png)
El Nino

Temperature (Celsius)

December 1990

Temperature (Celsius)

December 1997
## 2. Microwave vs. IR SST retrievals

<table>
<thead>
<tr>
<th>Factor affecting radiometry</th>
<th>Infrared radiometry</th>
<th>Microwave radiometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude of emitted radiation from the sea surface</td>
<td>[+ ] large ( B(\lambda, T) )</td>
<td>[- ] small ( B(\lambda, T) )</td>
</tr>
<tr>
<td>Sensitivity of brightness to SST</td>
<td>[+ ] large ( \frac{1}{B} \frac{\partial B}{\partial T} )</td>
<td>[- ] small ( \frac{1}{B} \frac{\partial B}{\partial T} ) (( B ) is proportional to ( T ))</td>
</tr>
<tr>
<td>Emissivity</td>
<td>[+ ] ( \varepsilon \approx 1 )</td>
<td>[- ] ( \varepsilon \approx 0.5 )</td>
</tr>
<tr>
<td>Clouds</td>
<td>[- ] Not transparent</td>
<td>[+ ] Clouds largely transparent (improvement at longer wavelengths)</td>
</tr>
<tr>
<td>Sea state (e.g., roughness)</td>
<td>[+ ] Independent</td>
<td>[- ] ( \varepsilon ) varies with sea state</td>
</tr>
<tr>
<td>Atmospheric interference</td>
<td>[- ] Requires complex correction</td>
<td>[+ ] Easily corrected with multichannel radiometer</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>[+ ] A narrow beam can be focused. Diffraction is not a problem in achieving high spatial resolution with a small instrument</td>
<td>[+ ] Diffraction controls the beam at large wavelengths. Large antenna required for high spatial resolution</td>
</tr>
<tr>
<td>Viewing direction on surface</td>
<td>[+ ] Surface radiance largely independent of viewing direction</td>
<td>[- ] ( \varepsilon ) varies with viewing direction</td>
</tr>
<tr>
<td>Absolute calibration</td>
<td>[+ ] Readily achieved using heated on-board target</td>
<td>[- ] Absolute calibration target not readily achieved</td>
</tr>
<tr>
<td>Presently achievable sensitivity</td>
<td>0.1 degree K</td>
<td>1.5 degree K</td>
</tr>
<tr>
<td>Presently achievable absolute accuracy</td>
<td>0.6 degree K</td>
<td>2 degree K</td>
</tr>
</tbody>
</table>